Electrophoretic Dielectric Coatings for Magnetic Switches*

H.C. Harjes, G.A. Mann, and D.J. Sharp

Sandia National Laboratories
Albuquerque, NM 87185

Abstract

In high magnetization rate magnetic switches, the insulation requirements are severe and in high average power applications the thermal management of core losses is a serious design issue. We have been investigating the possibility of using electrophoretic (EP) coating techniques to provide a viable alternative to dielectric films for insulation in such switches. The EP process is analogous to electroplating and as such offers advantages over other coating techniques including: excellent edge coverage, thicker coatings in areas of higher electric field stress, and the possibility of detecting and repairing any coating flaws or weak points in a secondary processing step. A continuous foil EP coating machine which is capable of coating Metglas at a rate of several feet/minute with a 2-24 μm thick methyl methacrylate coating has been constructed. In order to determine the dielectric strength of the coating in a wound geometry, capacitors have been wound with coated Metglas conductors and DC breakdown distributions have been obtained. Mean breakdown strengths in excess of 1 MV/cm have been observed. Experiments to demonstrate the effect of the second coating step on the breakdown distributions have also been conducted. In addition, the magnetic properties of small scale coated magnetic switch cores have been measured. Experiments have also be conducted on coated material at elevated temperatures. The results of these experiments will be presented.

Introduction

Continuously operating, high average power, repetitively pulsed accelerators are presently being considered for use in many applications (such as food sterilization, waste treatment, etc.). One of the principal switching technologies that is being investigated for use in the pulse compression systems of such accelerators is magnetic switches (ie. saturable reactors) [1]. In applications of this type, where component lifetimes and reliabilities are important issues, magnetic switches are attractive because they are solid state devices. However, further development in magnetic switch technology is required. In high average power applications, the thermal management of core losses is a serious design issue and, in high magnetization rate switches, insulation requirements are severe. Inter lamina voltages can be several 100s of volts and, at present, dielectric films (such as Mylar, Polycarbonate, Kapton, etc.) are the only insulation options. As in capacitors, when dielectric films are used for insulation, the film must be significantly wider than the metallic ribbon so that margins are formed on sides of the core. Since the thermal conductivities of the films are low, the margins form substantial thermal barriers and make the thermal management problem more difficult. In conventional magnetic cores (for motors, transformers, etc.), this problem is avoided by using dielectric coatings for insulation. These coatings, however, are only useful when inter laminar voltages are a few volts or less. This paper reports the results of our investigations into the use of electrophoretic (EP) coating techniques to provide a viable alternative to dielectric films for insulation in switches where the inter laminar voltages exceed a few volts.

EP coating techniques are widely used in industry and are described extensively in the literature [2,3]. Basically, electrophoresis is analogous to electroplating in that an electric field applied between two electrodes is used to cause small charged dielectric particles suspended in a liquid, to migrate to, and coalesce on the oppositely charged electrode as depicted in Fig. 1. After deposition, the coating must be cured so that the particles crosslink to form a tough coating that adheres well to the substrate. Since electrophoresis is driven by the electric field on the surface of the substrate, the EP coating technique has two important advantages over other coating techniques. First, the coating is conformal and tends to be thicker over edges and sharp surface protrusions where the surface electric field is higher. Second, any weak points or flaws in the coating can be detected and repaired in a second coating pass yielding a higher quality coating. Most EP coatings are thermally cured and during such a cure there is a tendency for the coating to soften and flow away from edges and high points in order to relieve surface tension. The first EP coating that was applied to Metglas (a styrene-acrylate requiring a 20 minute 200 C cure) exhibited this behavior and was not useful as a primary dielectric [4,5]. In order to avoid this problem, we have been investigating a, unique new EP coating that can be cured quickly by exposure to high power UV light. In this way the conformal nature of the coating is not degraded during the curing process. In addition, with this coating the design of a high speed continuous coating machine is simplified because a very long, in line, curing oven is not required. An effort to develop a continuous coating machine that can produce quantities of coated Metglas sufficient for testing in magnetic switch cores, has been ongoing for about two years. Initial results from this effort are described in reference [5] and recent results are presented below.

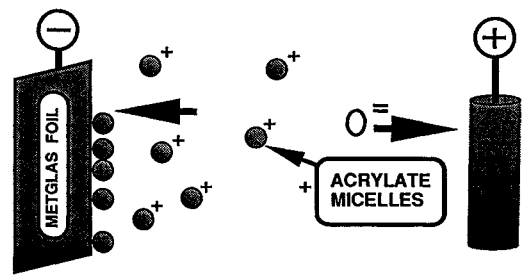

Fig. 1. The electrophoretic coating process is analogous to electroplating. The positively charged particles (ie. amine groups) suspended in solution are attracted to the negative cathode where they coalesce as a tacky coating.

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14. ABSTRACT
In high magnetization rate magnetic switches, the insulation requirements are severe and in high average power applications the thermal management of core losses is a serious design issue. We have been investigating the possibility of using electrophoretic (EP) coating techniques to provide a viable alternative to dielectric films for insulation in such switches.

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Prototype Coating Machine

The prototype coating machine, depicted in Fig. 2, is capable of continuously applying a coating (thickness adjustable 2-24 μm) to a metallic ribbon at a rate of up to 4 ft/min. As shown in the figure, the metallic ribbon begins on the supply spool, passes over a roller and down into the coating tank. Near the bottom of the tank, the ribbon passes over another roller, turns up, and moves into a stainless steel tube where coating takes place. The tube serves as the electrode opposite the ribbon in the coating reaction. The active coating length in the tube is about 2 ft. Upon leaving the tank excess coating solution is gently removed from the coated surfaces by an array of fine wiper blades. The ribbon then enters the curing chamber and passes in front of two UV light sources. After curing, the ribbon exits the curing chamber and is wound on the take-up spool. The take-up is driven by a computer controlled stepper motor which maintains the linear speed of the ribbon at a constant, operator selected, level. The ribbon's tension through the machine is controlled by adjusting the drag induced on the supply spool by a dynamic braking system.

Curing is performed in the 250-350 nm wavelength range at a dose of ~ 250 mJ/cm^2. The bulk of the curing is done by attenuated light from the first UV source (an electrodeless, microwave-excited, medium-pressure, mercury vapor plasma lamp). A second UV source is required because the surface polymerization of the coating is oxygen inhibited. Consequently, the surface monolayer of the coating is not completely cured by the first source and remains tacky. Without the second source, the coating sticks to itself when it is wound on the take-up spool and cannot be processed further. If this material is unwound (to straighten it or transfer it to another winding) numerous pullouts occur (ie. sections of the coating delaminate from the ribbon where the coatings in adjacent layers had stuck together). The second source

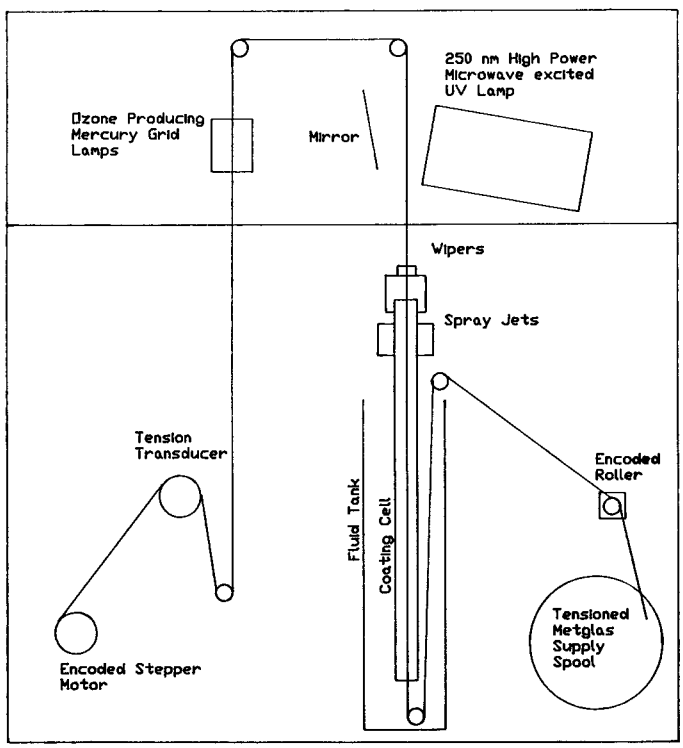

Fig. 2. Layout of the prototype coating machine.

(a low pressure mercury grid lamp) operates at shorter wavelengths (down to 180 nm) and produces ozone. The shorter wavelength light (which is primarily absorbed at the surface of the coating) in combination with the ozone (which oxidizes the surface of the coating) eliminates this problem.

The coating solution is an aqueous based colloidal suspension that contains acrylic oligomers, detergents, photocatalysts, and pH buffers. The colloid in the solution is sensitive to viscous shear and tends to coagulate in regions of high turbulence generating clumps of polymer in the solution. When these clumps become attached to the coated ribbon, the quality of the coating is compromised. The clumps are much thicker than the normal coating so they are not completely cured. As a result, they can cause pullouts when the material is unwound from the take-up spool. For this reason, pumping and flow of the coating solution should be minimized. Unfortunately, the prototype machine was designed so that a moderate flow rate is necessary between the coating tank and the solution reservoir to keep the solution at required operating temperatures (temperature is controlled by a heated water bath in which the reservoir sits). Consequently, without major modifications, this is a persistent problem in the prototype machine that can be managed to some extent but not eliminated. This problem is, however, not inherent in the process and may be solved with a machine design which eliminates turbulence in the solution.

The conventional mode for coating is to apply a DC voltage (40-100 V) between the cell electrodes and run the ribbon at a speed which allows the deposition to go to completion before the ribbon exits the solution. Since deposition is driven by electric field, it basically begins on the edges of the ribbon and works its way to the center (actually, the deposition rate is initially higher on the edges where the surface field is higher, but, as the coating accumulates, the process saturates and the center catches up). If the ribbon is removed from the solution before the process is complete, a non-uniform coating results. At room temperature, the thickness of a uniform coating is ~ 25 μm. To reduce this thickness, the temperature of the solution must be elevated. For example, a temperature of ~ 42 C is required to get a coating 7 μm thick. To increase the throughput rate of the machine (ie. the ribbon speed), the cell voltage can be increased so that the process goes faster. However, this requires a corresponding increase in the current density on the ribbon's surface (because essentially the same amount of charge must be deposited in a shorter time to give a completed coating of the same thickness). Above about 4 mA/cm^2, this is undesirable because an excessive number of bubbles become entrapped in the coating. During the coating process, hydrogen bubbles are formed at the ribbon (the cathode) due to the electrolysis of water. If a bubble is entrapped in the coating, a weak point is formed and the quality of the coating is reduced. Consequently, in the conventional mode of operation, the throughput rate of the machine is primarily limited by the current density that can be tolerated.

During our investigations, a superior, "pulsed", mode of coating has been identified. In the conventional mode, voltage is always on the cell and reactions (coating, electrolysis, etc.) are taking place continuously. In the pulsed mode, voltage is applied to the cell in pulses of a few seconds duration with significant dwell time between pulses. In our studies, the duty cycle has been in the range from 10-20 % so there is significant time for relaxation in the solution between pulses. The dwell between pulses is adjusted so that it corresponds to the time it takes the section of ribbon that was coated on the previous pulse to exit the coating

solution (ie. the time it takes for the ribbon to move a distance roughly equal to the effective coating length of the cell). In this way, fresh ribbon, with the exception of a short 2-3" long overlap section, is always in position in the cell to be coated by each subsequent pulse. The pulse amplitudes and widths are related and set as follows. When voltage is applied to the cell, the current rises rapidly to a level determined by the ratio of the applied voltage and the resistance of the solution between the steel tube and the bare ribbon. As the coating process reaches completion the resistance of the solution ceases to dominate and the current drops. The voltage is removed at this point. If the voltage amplitude is increased, the process goes to completion faster so the pulse width is decreased. This mode of operation has the following advantages over the conventional mode; 1) no observable bubbles are entrapped in the coating, 2) there seems to be no current density limitation so higher coating speeds are possible, 3) The coating seems to have better uniformity and edge coverage, and, 4) Thinner coatings (down to 2 μm) can be deposited. In this mode, coating speeds of 4 ft/minute have been demonstrated and the limitation is the time the ribbon must spend in front of the ozone curing lamp. The machine is stable in this mode of operation and long continuous runs have been demonstrated. For example, in one 8 hour run, a nominal 3 μm coating was applied to approximately 5 kg of Metglas 2605S-3A.

Results

The conformal nature of coatings produced on the prototype machine are demonstrated in the photographs of Fig. 3. Edge coverage is shown in the 1000x photograph and the coverage of a surface feature is shown in the 300x photograph. Both photographs are of a ~ 15 μm thick 2605-CO Metglas ribbon with a nominal 9 μm thick coating. This material was coated in the conventional mode at a rate of ~ 1.5 ft/min with a cell voltage of ~ 100 V and a solution temperature of 38 C. From this batch of material, tape wound capacitors were constructed to test the dielectric strength of the coating in a wound geometry. Each capacitor consisted of 2 coated ribbons ~ 9 ft long wound on a 1" OD fiberglass mandrel. Electrical connections were made to the ribbons by scraping the coating off in small areas outside the test region. The capacitors were then vacuum impregnated with fluorinert FC-77, and individually tested to failure with the application of a slowly rising voltage ramp (~ 200 V/s). The resulting breakdown distribution is shown in Fig. 4. The mean breakdown strength (1.5 MV/cm) is more than adequate for most magnetic switch applications but the distribution is relatively broad. This implies that the coating quality needs further improvement. The coating in these samples is also thicker than would be desirable in most magnetic switch applications. A breakdown distribution obtained in the same manner on pulsed coated samples is shown in Fig. 5. In this case, the coating thickness was ~ 2.5 μm, the pulsed cell voltage was 100 V, the solution temperature was 46 C, and the ribbon speed was 4 ft/min. The mean (0.8 MV/cm) is still good enough for most applications, but, as the scatter indicates, the quality of the coating needs much improvement.

As pointed out above, the prototype machine has some built in deficiencies that limit the quality of coatings it can produce. However, with the EP technique, coating flaws can, in principle, be detected and repaired in a second coating step. The second step is done at higher voltages so that weak points in the primary coating are exposed (ie. broken down). Then the exposed breakdown sites are repaired by the deposition of a coating that is thicker than the primary coating (because it is deposited at higher voltages and lower solution temperatures). Since the vast majority of the ribbon's surface is well insulated by the primary coating, very little overall deposition takes place in the second pass and much higher ribbon speeds are possible (the nominal thickness of the coating is only increased slightly). On the prototype machine, the ribbon speed was limited to 6 ft/min by the length of the ozone lamp. Curing on the second pass is a bit more difficult. The locally thicker coatings over breakdown sites must be cured well enough that they do not induce the sticking problem described above, and care must be taken that the primary coating is not "overcooked". If the primary coating is exposed to too much UV light it becomes brittle and when the ribbon is bent it tends to crack and delaminate.

As was the case in the development of primary coating techniques, the quality of second pass coatings will improve significantly as the coating technique is refined. The breakdown distribution shown in Fig. 6 is a result from one of our first second pass investigations. In this case, the secondary coating was applied with a simple DC coating cell voltage. A comparison of figures 5 and 6 shows the improvement that was achieved with the second pass. Both sets of capacitors were wound with material from the same primary coating batch (parameters described in Fig. 5). The second pass yielded some improvement in mean breakdown strength (.8 to 1.27 MV/cm) and a significant increase in the breakdown threshold. However, the distribution is still relatively broad.

To be useful in a high average power magnetic switch, the coating must not only have good dielectric strength, but, also be able to endure the temperatures in the core and not significantly degrade the magnetic properties of the Metglas. For the application

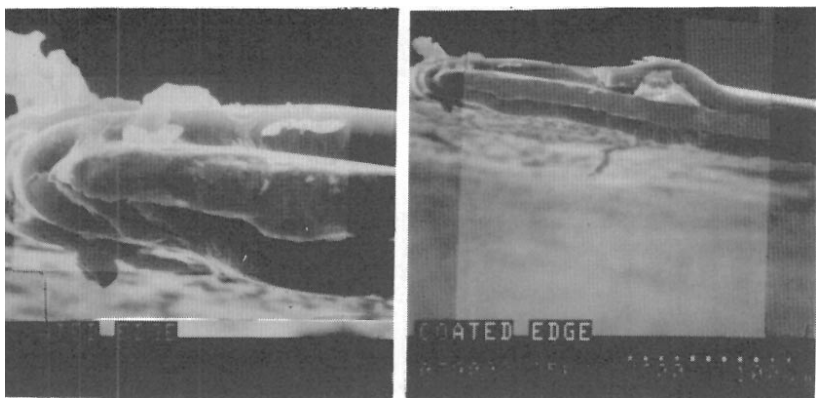

Fig. 3. SEM micrographs demonstrating the conformal nature of the coating. Edges are covered and particles on the substrate surface are covered.

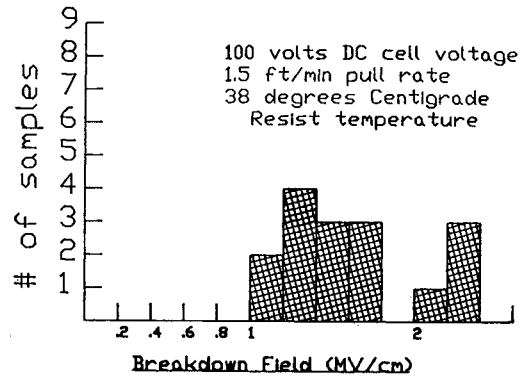

Fig. 4. DC breakdown distribution for capacitors wound from Metglas with a nominal 9 μm thick coating applied with the conventional EP coating technique.

described in [1], magnetic core temperatures of ~ 100 C are expected. In order to get some idea about how the coating would behave at 100 C, a simple experiment was conducted. A 6" long section of coated Metglas (nominal coating thickness 3 μm) was immersed in a heated oil bath. The temperature of the bath was elevated to 100 C and held there for over 24 hours. Then the temperature was increased to 150 C and maintained for about 8 hours. After the test, the sample was inspected and no signs of degradation were observed. The only noticeable change in the coating was that the dye, which is included in the coating to give it a blue color, had leached out. More rigorous tests will be required to determine the long term stability of the coating at elevated temperatures, but this first test indicates that the coating is worthy of further testing.

When some coatings are applied to Metglas, the magnetic properties of the material are degraded to the point that the material is not useful [6]. Some tests have been done to see if the EP coating has any effect on the magnetic properties of Metglas and thus far no effects have been observed (B-H loops for both coated and uncoated as-cast 2605S-3A Metglas have been measured and they were the same to within measurement accuracy). However, only as-cast Metglas alloys have been tested because these are the only alloys that have coated on the prototype machine (annealed alloys are very brittle and have a much greater tendency to break when under tension). In most applications, annealed alloys are preferred because they have superior magnetic properties. The properties of annealed alloys are optimized by relieving stresses on the material, so they are likely to be more susceptible to degradation than the as-cast alloys. The thermally cured styrene-acrylate EP coating was applied to annealed 2605-CO Metglas and no degradation was observed. The very high anisotropy energy of the CO alloy, however, makes it unique in its ability to withstand stresses. Consequently, although indications are good, further testing in this area will be required.

Summary

Electrophoretic coating techniques are being investigated to determine if such coatings might provide a viable insulation option for high average power magnetic switches in which inter laminar voltages exceed a few volts. A prototype machine capable of continuously applying a unique, UV curable, coating to Metglas ribbon in thicknesses from 2-24 μm at a rate of 4 ft/min has been developed. The conformal nature of the coating has been demonstrated and DC breakdown distributions with means up to 1.5 MV/cm have been obtained. A superior, pulsed voltage technique has been developed for applying primary coatings and further improvements in coating quality have been demonstrated by subjecting coated ribbon to a secondary coating step. The coating showed no signs of degradation in a simple thermal test at up to 150 C. In addition, B-H measurements of coated Metglas have shown no indication that the coating has a significant effect on magnetic properties.

The quality of the coatings that can now be produced seems to be primarily limited by deficiencies in the prototype machine design. For this reason and because all of the results to this point have been positive, a new coating machine has been designed and is presently under construction. It will not have the deficiencies that have been identified in the prototype and will be capable of coating ribbon at a rate of up to 60 ft/min. Further refinements in coating techniques will take place on this machine and higher quality coatings are expected. More rigorous thermal and magnetic property testing will be conducted on ribbon from this machine. If results continue to be positive, several of the magnetic switches in the RHEPP (Repetitive High Energy Pulsed Power project) pulse compression system [1] will use coated Metglas produced on this machine.

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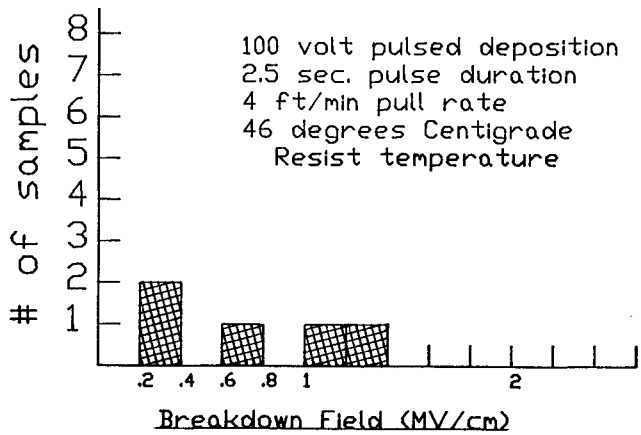

Fig. 5. DC breakdown distribution for capacitors wound from Metglas with a nominal 2.5 μm thick coating applied with the pulsed coating technique.

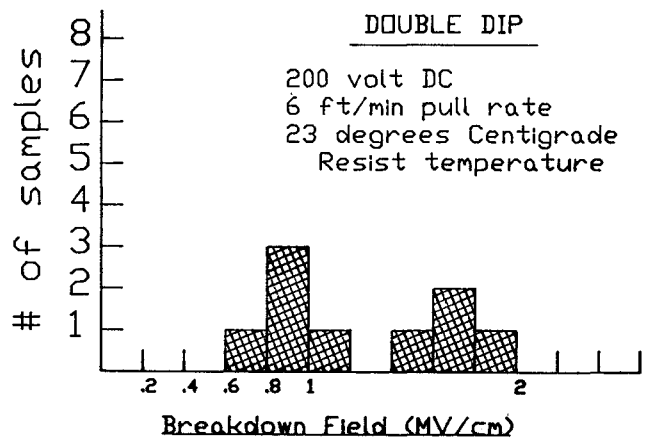

Fig. 6. DC breakdown distributions on capacitors wound from coated Metglas that was subjected to a secondary coating step.